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SOURCE OF CP VIOLATION FOR THE BARYON ASYMMETRY OF THE UNIVERSE

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We give a description of why the existence of a fourth generation is likely to provide enough CP violation for baryogenesis, and trace how this observation came about. We survey the current experimental and theoretical pursuits and outline a research agenda, touching upon unitarity violation and very heavy chiral quarks, and comment on how the electroweak phase transition picture might be altered.

Keywords: CP violation; baryon asymmetry of the Universe; fourth generation.

1. Introduction

It was the great physicist Andrei Sakharov who made the link between the puzzling experimental discovery of CP violation (CPV), with the even more puzzling Baryon Asymmetry of the Universe (BAU): the absence of antimatter from the observable Universe. The BAU puzzle is as follows. At the Big Bang, equal amounts of matter and antimatter ought to be produced. Of course, they will mutually re-annihilate as the Universe cools, and indeed this feeds eventually the Cosmic Microwave Background radiation. But why then is *any* matter left, and at roughly 10^{-9} of the primordial production? Sakharov's three conditions[1] for this to occur is:

(i) Baryon Number Violation;
(ii) CP Violation;
(iii) Deviation from Equilibrium.

It is truly remarkable that the Standard Model (SM) satisfies condition (i) in a nontrivial way, provides CPV phase(s) in the charged current through quark mixing, and one is hopeful for nonequilibrium through the "condensation" that

lead to spontaneous electroweak symmetry breaking (EWSB). Alas, the SM seems *insufficient* in conditions (ii) and (iii): the amount of CPV in the three generation Kobayashi–Maskawa model falls far short from what is needed, as we shall see in the next section, while the phase transition seems too smooth because the Higgs boson is not light enough.

It has therefore been popular to invoke "Baryogenesis through Leptogenesis", namely that BAU occurs first through lepton–antilepton imbalance, then transferred to baryons by the electroweak forces in SM. I offer some comments. Leptogenesis based on traditional seesaw mechanism for generating tiny neutrino mass, through right-handed Majorana scale at 10^{12} GeV or higher, is rather beautiful. However, it appears to be "metaphysics", in the sense that it can not be experimentally tested in the foreseeable future! Then, there are the Type II and III, etc. seesaw models that bring in more assumptions, in good part to make them more accessible at the LHC (or future machine), and the models become less beautiful.

This pushes the traditional-minded physicists like myself to yearn for the SM, since it satisfies all *necessary* conditions of Sakharov, albeit insufficiently in two of them. With the caution that we have no right that "the theory of our time" would touch so deeply the core to the Universe (and Our Existence), we do like to ask:

Can one restore TeV Scale Baryogenesis?

What about the Source of CP Violation?

This talk tries to touch upon these profound issues, especially on the CPV front.

2. Tracing a Thread in the Tapestry: CPV on Earth

CP violation was forced upon us by experimental discovery, which caused the pure minds such as Dirac to depress. But it in fact opened our minds further to deeper truths on the antimatter world that Dirac himself uncovered for us.

2.1. *Experimental knowledge of CPV*

Sakharov wrote down his conditions in 1966 (published in 1967), which was clearly stimulated by the experimental observation,[2] in 1964, of CP violation in $K_2 \to \pi^+\pi^-$ decay, now interpreted as the physical K_L^0 meson having a small admixture of the K_1 state. The 1980 Nobel prize was awarded to James Cronin and Val Fitch for their experimental discovery. The pursuit was on for the "direct" CPV (DCPV), i.e. in decay, within the kaon system, which was finally established[4] in 1999.

It was the two (then) young Japanese physicists, Makoto Kobayashi and Toshihide Maskawa (KM), who pointed out[3] in 1972 (published in 1973) that if a third generation (3G) of quarks exist, then a unique CPV phase appeared in the 3×3 quark mixing matrix governing the charged current. It is remarkable that, at that time, even two generations were not completely established. But within a few years, the c quark, the τ lepton, and the b quark were all discovered, although it took another 18 years before the top quark was discovered at the Tevatron.

But the main issue for KM was CP violation. The picture was convincingly confirmed[4] between the Belle and BaBar experiments in 2001, and the pair was awarded 1/2 the 2008 Nobel prize. What is remarkable, and reflecting the prowess of these B factory experiments, is that DCPV in the B system, in the form of difference in rate for $B^0 \to K^-\pi^+$ vs. $\bar{B}^0 \to K^+\pi^-$, was the highlight observation of 1994. It came a mere three years after the Nobel prize defining measurement of mixing-dependent CPV (TCPV) in 2001, which is in contrast to the tortuous path of 35 years for the kaon system. We will discuss further developments which sprang from the observation of DCPV in the B system, in the next section.

2.2. *KM model and its limitations*

2.2.1. *Complex dynamics: KM sector of SM*

What KM pointed out was that, while the 2×2 quark mixing matrix of the charged current (weak coupling g modulated as gV_{ij}) is real, a unique, irremovable phase appeared in the 3×3 generalization. The unitary matrix V can be parameterized[4] in the form where the 2×2 sector is real to very good approximation, while it is traditional (a phase convention) to put the unique CPV phase in the V_{ub} element, which is then reflected in the V_{td} element by unitarity, or $VV^\dagger = V^\dagger V = I$.

Unitarity of V correlates multiple physical measurables involving flavor and CPV. One such condition is the relation

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\,, \tag{1}$$

from $\{VV^\dagger\}_{db} = 0$. The KM condition for CPV is that the triangle formed by Eq. (1) should be *nontrivial*, i.e. the *area* A of the triangle should not vanish. Remarkably, while many relations, or triangles, similar to Eq. (1) can be written or formed, they all have the same area A, reflecting the unique CPV phase in the 3G KM model.

For Eq. (1) to be *nontrivial*, the sides of the triangle should not be colinear. It was measuring the finite angle between $V_{td}V_{tb}^*$ and $V_{cd}V_{cb}^*$ (the latter defined real in standard[4] convention) in 2001, together with knowledge of the strength of the sides $V_{ud}V_{ub}^*$ and $V_{cd}V_{cb}^*$ as well as many other flavor/CPV observables, that confirmed the nontrivial realization of Eq. (1), hence the CPV phase of the KM model.

2.2.2. *Jarlskog invariant and CPV*

Besides the nontrivial realization of Eq. (1), a further subtlety can be inferred from the original KM argument: all like-charged quark pairs must be nondegenerate in mass! Otherwise, if their is just one pair of, say d and s quarks, that are degenerate in mass, then one finds a phase freedom that can absorb the single CPV phase, and effectively one is back to the two generation case with vanishing CPV.

An algebraic construction, known as the Jarlskog invariant,[5] nicely summarizes the nontrivialness of Eq. (1) and the nondegeneracy requirement:

$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)\, A\,, \tag{2}$$

where A is the triangle area as defined before, while the appearance of every (like-charged) pair mass difference ensures that J would vanish with the degeneracy.

J in Eq. (2) is not merely a transcription of the wording of previous prerequisites, but has powerful algebraic roots. It can be derived from $J \equiv \mathrm{Im}\,\det\left[m_u m_u^\dagger,\ m_d m_d^\dagger\right]$ for the case of 3G. Thus, in terms of the Jarlskog invariant, one has

$$\text{CPV} \quad \textit{iff} \quad J \neq 0.$$

2.2.3. *The "Lore" for insufficient BAU from CPV in KM*

In his Nobel lecture, Kobayashi admitted that "Matter dominance of the Universe seems requiring new source of CP violation",[6] i.e. beyond the 3G model he and Maskawa presented. In fact, it is known[7] that J seems short by at least 10^{-10}! Let me give[8] a heuristic, dimensional argument for why this is so.

The issue of BAU is not so much the disappearance of antimatter, i.e. the apparent $n_{\overline{\mathcal{B}}}/n_\gamma \cong 0$, but that *some*, in fact a tiny amount of matter remain (which contains *us*!!), namely $n_{\mathcal{B}}/n_\gamma = (6.2 \pm 0.2) \times 10^{-10}$ as measured by WMAP, which is the 10^{-9} quoted earlier in the Introduction. Thus, the actual *asymmetry*, or BAU, is 100%, but the challenge is to explain $n_{\mathcal{B}}/n_\gamma \neq 0$, and to account for the tiny amount. Note that this is a dimensionless number, while J of Eq. (2), the source of CPV, carries 12 mass dimensions. Normalizing by $T \sim 100$ TeV, the electroweak phase transition temperature (equivalently one could normalize by the v.e.v.), then inserting all quark masses gives $J/T^{12} \sim 10^{-20}$, which can now be compared with $n_{\mathcal{B}}/n_\gamma \sim 10^{-9}$. This is the "Lore" that the CPV in KM model is too small by at least 10 billion.

Further inspection of Eq. (2) shows that $A \sim 3 \times 10^{-5}$ as measured, though small, is not the major culprit. The real issue is that quark masses (except m_t) are too small: the powers of $m_s^2\, m_c^2\, m_b^4$ as compared to T^8 are just too small!

3. Soaring to the Heavens: 3G → 4G

The way the previous section ended has already planted the seed for the main observation of this section. But let us trace through the way it actually came about. In effect, it arose from broadening of the Mind by *Nature* writing.

3.1. *The Thread again*

Experiment is our modern age Delphi *oracle*, and what it utters sometimes has more than one interpretations.

The Thread that lead was the hint, at 2.4σ level for Belle,[9] that emerged with the 2004 observation of DCPV in $B^0 \to K^+\pi^-$: the asymmetry $A_{K^+\pi^0}$ for the analogous charged $B^\pm$ meson decays seemed different from $A_{K^+\pi^-}$ for neutral B meson decays. With similar effect seen by BaBar, the plenary speaker at ICHEP 2004 from Belle, Yoshi Sakai, questioned[10] whether this hinted at large electroweak

(or Z^0) penguin, hence implied New Physics. The point is that a virtual Z^0 could convert to a π^0, but not a charged pion, hence the Z^0 penguin contributes to $B^\pm \to K^\pm\pi^0$, but is less effective for $B^0 \to K^\pm\pi^\mp$. But if $P_{\rm EW}$ is the culprit, then it must arise from New Physics, as there is vanishing CPV phase in $b \to s$ penguin transitions within SM, as it is governed by $V_{ts}V_{tb}^*$, which is effectively real for 3G.

Shocked while writing the first draft of this Belle paper — the counterintuitive difference was never predicted — it reminded me of my first B paper,[11] which was on the related electroweak penguin process $b \to s\ell^+\ell^-$ (the $\ell^+\ell^-$ takes the place of the π^0). Prior to that paper, G_F power counting had lead people to discard the Z^0 penguin as compared to the photonic penguin. At G_F^2 order, the former should be small compared with the latter, which is at αG_F order. Or so it seems: since G_F has -2 mass dimension, there should be some m^2 to make the comparison with the photonic penguin. One would again dismiss it by taking $m \sim m_b$ naively. However, it turns out that $m \sim m_t$, the top quark in the loop that could be heavy.

Direct computation showed that for large m_t ($\gtrsim 2M_W$), the $b \to s\ell^+\ell^-$ rate grew almost like m_t^2, and the heavy quark effect is *nondecoupled*. We should be familiar with the usual decoupling theorem, where heavy masses are decoupled from scattering amplitudes, such as in QED and QCD, since they only appear in propagators. However, *nondecoupling* appears because Yukawa couplings $\lambda_Q \propto m_Q/v$, where v is the v.e.v., appear in the numerator and can counteract the propagator damping. Thus, the nondecoupling phenomena is a *dynamical* effect, and is a subtlety of spontaneously broken *chiral* gauge theories.

My first B paper turned out to be also my first four generation (4G) paper, where the nondecoupling effect of 4G t' quark could be easily more prominent. So, I went ahead and demonstrated with two associates the efficacy of the 4G t' quark, that it could[12] drive apart $A_{K^+\pi^0}$ from $A_{K^+\pi^-}$, for a range of parameters in $m_{t'}$ and $V_{t's}^*V_{t'b} \equiv r_{sb}\, e^{i\phi_{sb}}$. As a corollary, since the Z^0 penguin and the box diagram are cousins of each other, the CPV effect of nondecoupling of t' in $b \to s\, Z^0$ penguin should have implications for CPV in the $\bar{B}_s$–B_s mixing via the box diagram, which we will discuss in the next section.

3.2. *Nature writing*

Because direct CPV, including the DCPV difference $\Delta A_{K\pi} \equiv A_{K^+\pi^0} - A_{K^+\pi^-}$, are simple "bean counts", the Belle experiment decided to write a paper for the journal *Nature* to highlight the effect. With even CDF joining the measurement, the asymmetry $A_{K^+\pi^-}$ became firmly established around -10%. Therefore, although $A_{K^+\pi^0}$ was not yet firmly established, the unanticipated $\Delta A_{K\pi}$, measured now by a single experiment (Belle) to be[13] $+0.164 \pm 0.037$ with 4.4σ significance, is *very large*: the difference is larger than the already impressively large $A_{K^+\pi^-} \simeq -10\%$ (cf. $|\varepsilon'_K| \sim 10^{-6}$).

Although "the oracle spoke", the effect put forward by this paper was not widely accepted as indicating New Physics. Perhaps the particle physics community treat

Nature announcements no better than the *New York Times*. There was also the issue that large $\Delta A_{K\pi}$ could be interpreted as an enhanced color-suppressed tree amplitude C that has a considerable strong phase difference with T, the regular tree amplitude. But the actual "*Nature* writing", in "explaining CPV to biologists", got me "out of my mind", which I turn to in the next subsection.

3.3. *Providence*

The heuristic, dimensional analysis argument for why the KM mechanism for CPV falls far short of BAU makes clear that the culprit is the smallness of lighter quark masses. As we tried to convey to the editor of *Nature* the relevance of large $\Delta A_{K\pi}$ to readers of their journal, one day late summer 2007, it occurred to me that, if there is 4G and one shifts by one generation in Eq. (2) for the Jarlskog invariant J (recall that one needs 3 generation for the KM mechanism of CPV, hence one is discarding the first generation for a 2-3-4 world), one gets

$$J^{sb}_{(2,3,4)} = (m_{t'}^2 - m_c^2)(m_{t'}^2 - m_t^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_s^2)(m_{b'}^2 - m_b^2)(m_b^2 - m_s^2)A^{sb}_{234}, \quad (3)$$

where one sees that, besides $m_t^4 \to m_{t'}^2(m_{t'}^2 - m_t^2)$, the extreme suppression factor of $m_s^2\, m_c^2\, m_b^4$ is replaced by $m_b^2\, m_t^2\, m_{b'}^4$. Even for A^{sb}_{234} comparable in strength to A (numerical analysis of $\Delta A_{K\pi}$ suggested[12] a factor of 30), this lead to a gain of 10^{13}–10^{15} for $J^{sb}_{(2,3,4)}$ over J for 3G, for $m_{b'},\ m_{t'} \in (300,\ 600)$ GeV, and clearly removes the verdict that KM mechanism for CPV falls far short of observed BAU.

The fact that now one seems to have enough CPV within SM, at the cost of 3G $\to$ 4G, makes one wonder whether *Mother Nature* might actually use this? True enough, it was amusing to receive the arXiv number of ".1234", a sure sign of Providence, when I posted the paper from a Zurich hotel room in March 2008, before heading for Moriond. But then, a probability of 10^{-3} is nothing compared to the gain of a thousand trillion (10^{15}). As an anecdote, the paper eventually appeared in the *Chinese Journal of Physics* (published in Taiwan) in 2009.

4. 2007–2010: 4G Rehab

The stiffness one faced on 4G studies were not without reason: the fourth generation had become rather exotic with data from LEP. For the detailed early numeric study of 4G effect on $\Delta A_{K\pi}$, I was lucky to publish two papers in *Phys. Rev. Lett.* The first one in 2005 may be because it was a timely response to some emergent phenomenon from the B factories. For the second,[14] applying PQCD factorization at next-to-leading order (NLO), may be due to its sheer technicality ...

But one could clearly feel the rehabilitation of 4G during the year of 2010, perhaps even becoming a mild fashion. Such was not the situation back in 2007.

4.1. *Why not 4G?*

Let me use the words of an experimentalist, Alison Lister[15] of CDF (and now ATLAS), at the ICHEP 2010 conference. Why not four generations? There are[4]

two issues:

- Z-width measurement from LEP: perfect fit with only three light neutrinos;
- Electroweak effects: S, T fits (severely) constrain available 4G phase space.

For the first, traditional, fourth generation show stopper, Lister counters that the true constraint is $m_{\nu_4} > M_Z/2$. Let me add to that, by first changing the notation of the possible new fourth neutral lepton and denote it as N^0, to avoid the connotation of lightness that comes with "ν_4". It should be emphasized that, since the discovery of atmospheric neutrino oscillations in 1998,[4] we know that neutrinos have mass, implying the existence of another mass scale. This logically refutes the traditional strict interpretation that a fourth light neutrino is excluded by LEP data. It is indeed excluded, but we already know there is New Physics in the neutrino or neutral lepton sector. We then stress that the neutral lepton N^0 is very hard to access in the near future at the LHC (or through neutrino oscillations), unless it is of Majorana nature with v.e.v. scale masses.

The second problem of electroweak (EW) S and T constraints are potentially more serious. But, as pointed out by Kribs, Plehn, Spannowsky and Tait in 2007,[16] these constraints have been over-interpreted (by PDG): 4G is in fact allowed by EW radiative corrections, and one could even argue that sometimes it gives better agreement together with a *heavier* Higgs boson. This has been further followed up by Chanowitz,[17] and with the response[18] from Erler and Langacker not fully refuting, it is a main cause of the mini-revival of 4G in the past few years.

4.2. *Touching more Earth: CPV in B_s system*

There are other reasons for the gradual move to more favorable view (as compared to the past) on 4G, arising from flavor and especially CPV studies of the B_s system. I am fond of quoting the CDF citation[19] of myself "George Hou predicted the presence of a t' quark with mass ... to explain the Belle results and predicted *a priori* the observation of a large CP-violating phase in $B_s \to J/\psi\,\phi$ decays".The wording "predicted *a priori*" is especially amusing, and should be a reminder to theorists. In any case, this refers to my work on the corollary of large $\sin 2\Phi_{B_s}$ for the t' quark interpretation of the $\Delta A_{K\pi}$ "anomaly".

We showed in PQCD at LO in 2005,[12] then at NLO in 2007,[14] that 4G can in principle generate $\Delta A_{K\pi}$. The prediction in 2005 was that $\sin 2\Phi_{B_s}$, defined as the CP phase of the $b\bar{s} \to s\bar{b}$ box diagram (mediating $\bar{B}_s \to B_s$, similarly defined as $\sin 2\Phi_{B_d} \equiv \sin 2\phi_1 \equiv \sin 2\beta$ for $\bar{B}_d \to B_d$), would be in the range of -0.2 to -0.7. This was refined[20] in 2007 to -0.5 to -0.7 after Δm_{B_s} was observed by the CDF experiment in 2006. The reason that CDF jovially quoted me in summer 2008 is because three consecutive measurements at the Tevatron ($\sin 2\beta_s \equiv -\sin 2\Phi_{B_s}$ for CDF, and $\sin\phi_s \equiv \sin 2\Phi_{B_s}$ for D∅) gave large central values. The combined significance, however, had dropped to 2.1σ by summer 2009.[21]

My 2005 and 2007 studies were based on $m_{t'} = 300$ GeV. As the mass bounds

were rising, I was working with an associate on a 500 GeV update. The experimental developments in 2010 were actually mixed, but also turned up the heat. First, it was the DØ announcement[22] in May of significant a_{sl}^s (something akin to the ϵ_K but for the B_s system). This strengthened the indication of deviation from SM (i.e. 3G). I had commented,[23] with an associate, on the previous round of DØ studies, and had mentioned that 4G could lead to a sizable a_{sl}^s. With the new result, which gives the same central value but improves the errors by a factor of two, I did not want to write another paper. But I placed a comment in a conference talk,[24] that the new DØ result, if true, would violate a bound already stressed in Ref. 23, hence probably suggests hadronically enhanced (i.e. OPE violating) $\Delta\Gamma_s$ values. Then came the CDF result[25] on $\sin 2\beta_s$ that was less discrepant with SM, implying a smaller value. In the meantime, and prior to the CDF update, I had pointed out[26] that the expected value for $\sin 2\Phi_{B_s}$ was weaker (nominally -0.3) for the heavier $m_{t'} = 500$ GeV case.

So, the fourth generation "prediction" is still robust, but would now need LHCb to verify. It must have been rather sad for the B workers at CDF (who had remeasured Δm_{B_s}) when they opened the box for 5.2 fb^{-1} data. Had the added data firmed up the 2008–2009 indication, it would allow the possible capture of $\sin 2\Phi_{B_s}$ at the "evidence" or better level with the full Tevatron dataset, hence would have constituted a New Physics discovery. With the low central value, and with already half the dataset of Run II used, there is no hope for any future claim to "evidence", and the torch is thereby passed to LHCb. On the theory front, the papers[27] by Soni and associates, Buras and associates, and Lenz and associates in the first half of 2010, together with other studies, clearly ushered in the "4G rehabilitation".

4.3. *The Pursuit, and its dilemma/opportunity*

In retrospect, actually much if not most highlights of flavor and CPV physics were learned through the *nondecoupling* effect: the GIM mechanism, the charm mass, ε_K from the $s\bar{d} \to d\bar{s}$ box; heavy top as inferred from large B_d mixing ($b\bar{d} \to d\bar{b}$ box), with the consequent CPV phase measurement, and the small ε'/ε due to $s \to d$ Z-penguin and Z-penguin enhanced $b \to s\ell^+\ell^-$ rate. *All from boxes and Z penguins!* If there is 4G, we already saw the possible effect on B_s system. Other measurables to watch would be $A_{\rm FB}(B \to K^*\ell^+\ell^-)$, redux of $\sin 2\phi_1/\beta$ and ε_K, $Z \to b\bar{b}$, maybe $\sin 2\Phi_D$, and especially $K_L \to \pi^-\nu\nu$ (KOTO experiment). That is, an agenda for all aspects of flavor physics and CP violation, all as a consequence of large Yukawa couplings!

But, nothing can replace direct search for the 4G t' and b' quarks, and we are on the verge of transit from the Tevatron to the LHC era.

The pursuit at the Tevatron has been vigorous, with the mass bound ever rising. The current CDF limit is[15]

$$m_{t'} > 335 \text{ GeV}, \quad 95\% \text{ C.L.}, \tag{4}$$

based on 4.6 fb^{-1} data. But a persistent irritation since earlier analyses with smaller

datasets, is the weakening of the bound from what was expected, due to excess events at high $M_{\rm reco}$ (reconstructed mass) and H_T (a scalar sum of transverse energies). With DØ now observing something similar[15] but giving a weaker bound, it is not clear whether the excess events are due to common misunderstanding of background, or something genuine. CDF has pursued the much cleaner signature of same-sign dileptons via $b'\bar{b}'$ pair production, followed by $b' \to tW$ decay, reaching mass bounds similar[28] to Eq. (4) for b'.

With the successful 2010 run of LHC at 7 TeV, the table is turning to the ATLAS and CMS experiments. Hereby lies both a dilemma, as well as an opportunity. With just 1 fb^{-1} data, the bound on 4G masses at LHC would reach beyond 500 GeV,[29] which is roughly the unitarity bound[30] where *perturbative* partial wave unitarity, or probability conservation, breaks down. How does one continue the pursuit? With the available energy at the LHC, clearly one should not stop searching at 500 GeV. Besides the need for theoretical guidance for continued search, precisely because perturbation theory would breakdown, one comes face to face with some rather interesting issues related to *strong* Yukawa couplings, the origin of the aforementioned nondecoupling.

The most tantalizing conjecture is:

Could EWSB be due to b' and t' near or above the unitarity bound?

A conjecture, traced to Nambu (the recipient of the other half of 2008 Nobel prize), is that perhaps $\bar{Q}Q$ could develop a v.e.v., i.e. condense, by large Yukawa coupling!(?) To seriously address these issues, one needs a nonperturbative platform of study, and the only one we know, is on the lattice. A study of the strong Higgs-Yukawa sector on the lattice has therefore been initiated.

4.4. *The “3 + I” approach — a research agenda*

Without further ado, let me outline an approved five-year (starting August 2010) research program, what I dubbed the “**3 + I**” approach under the title of “Beyond Kobayashi-Maskawa — Towards Discovery of 4th Generation Quarks at the LHC”.

The “**3**” is a three-pronged approach to the associated physics. Naturally, there is the direct search with the CMS detector. We have also purposefully built up a new theory group, both for the LHC era in general, and to provide phenomenology support for the experimental effort. The third arm is a consortium of Taiwan and DESY-Zeuthen on the aforementioned strong Higgs-Yukawa on the lattice. Note that results from the lattice study would become desperately needed to pursue beyond the expected 2011 data, which would touch and could reach beyond the unitarity bound.

This approved five-year project has loftier experimental goals: to uplift the past platform into the full, long term run plan of the LHC. As such, one needed to expand beyond the Taiwan CMS contribution to the Preshower subdetector during the past decade. We were lucky to become part of the CERN/Taiwan center, one of the three (the other two are PSI/ETHZ and DESY/Aachen/Karlsruhe) centers

for module production for the CMS Pixel Upgrade Phase I, targeted for completion in 2016. Such "deeper" involvement within CMS longer term hardware effort will certainly assure our longer term physics program.

5. Conclusion: Know in 3–5(–7) Years

The most important point of this talk is Eq. (3), where the 1000 trillion (10^{13}–10^{15} for $m_{b'}$, $m_{t'}$ ranging from 300 to 600 GeV, with A^{sb}_{234} not less in strength than A) gain in CPV over 3G, hence likely enough CPV for BAU. It makes one suspect that *maybe there is a fourth generation!* We have discussed flavor/CPV aspects of, as well as direct search for, 4G quarks. The Tevatron should still be watched, but clearly the mantle has passed to the LHC:

- $\sin 2\Phi_{B_s}$ "Confirmation" — should be "easy" at LHCb;
- b' and t' Discovery — straightforward, and able to cover full terrain,

except for unitarity bound issues for the latter.

Within 3 to 5 years, maybe 7, we should know the answer. That is one advantage of 4G vs. other New Physics scenarios (e.g. related to BAU). And if we find the answer in the affirmative, we may have brought down Heaven on Earth, namely that we might attain realistic understanding of BAU, from "the theory of our time".

Within a matter of years, direct search at the LHC for heavy b' and t' quarks would have hit the unitarity bound. How *Nature* cures this perturbative malady may shed light on the source of electroweak symmetry breaking, and the existence and nature of the Higgs boson. That would be a huge bonus to the 4G program.

6. Postscript: What about the Strength of Phase Transition?

One may perceive a remaining obstacle for electroweak baryogenesis, even if 4G is established, i.e. condition (iii) of Sakharov, or departure from equilibrium. In the standard Higgs potential approach, the strength of phase transition is controlled by the cubic term in the Higgs field. For $m_H > 72$ GeV, which seems the case experimentally, Kajantie, Laine, Rummukainen and Shaposhnikov[31] have done a lattice study to show that the transition is only a crossover. With 4G and without any new bosons, it is still insufficient. The basic reason is that the cubic term receives only bosonic contributions, and the W and Z in SM are too light. The remedy is therefore to put in more bosons, such as light stop in supersymmetric framework.

I mention some caveats. First, the "Nambu $\bar{Q}Q$ pairing", or condensation due to strong Yukawa, should affect the cubic term. Second, the (multi-)Higgs field(s) would be likely composite with strong Yukawa couplings. Finally, the standard approach treats the Higgs as elementary, i.e. structureless. Composite Higgs, which has not been seriously studied for phase transitions at finite temperature, would change the scenario.

Could the *nonperturbative* Yukawa couplings of 4G quarks save the day? This is another issue to be studied by the lattice Higgs-Yukawa effort.

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